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Summary Report

# ENERGY CONSUMPTION CHARACTERISTICS OF TRANSPORTS USING THE PROP-FAN CONCEPT

NOVEMBER 1976


BOEING COMMERCIAL AIRPLANE COMPANY
PRELIMINARY DESIGN

P.O. BOX 3707 SEATTLE, WASHINGTON 98124



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16. Abstract
The fuel saving and economic potentials of the prop-fan high-speed propeller concept were evaluated for twin-engine commercial transport airplanes designed for 3333.6 km (1800 nmi) range, 180 passengers, and Mach 0.8 cruise. A fuel saving of 9.7% at the design range was estimated for a prop-fan airplane having wing-mounted engines, while a 5.8% saving was estimated for a design having the engines mounted on the aft body. The fuel savings and cost were found to be sensitive to the propeller noise level and to aerodynamic drag effects due to wing-slipstream interaction. Uncertainties in these effects could change the fuel savings as much as ± 50%. A modest improvement in direct operating cost (DOC) was estimated for the wing-mounted prop-fan at current fuel prices. This improvement could become substantial in the event of further relative increases in the price of oil. The improvement in DOC requires the achievement of the nominal fuel saving and reductions in propeller and gearbox maintenance costs relative to current experience.

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# 1.0 SUMMARY

## 1.1 GENERAL

The fuel saving and economic potentials of the prop-fan, a high-speed advanced technology propeller proposed by Hamilton Standard, have been evaluated for application to twin-engine Mach 0.8 commercial transport airplanes designed for 3333.6 km (1800 nmi) range with 180 passengers. Three designs were analyzed:

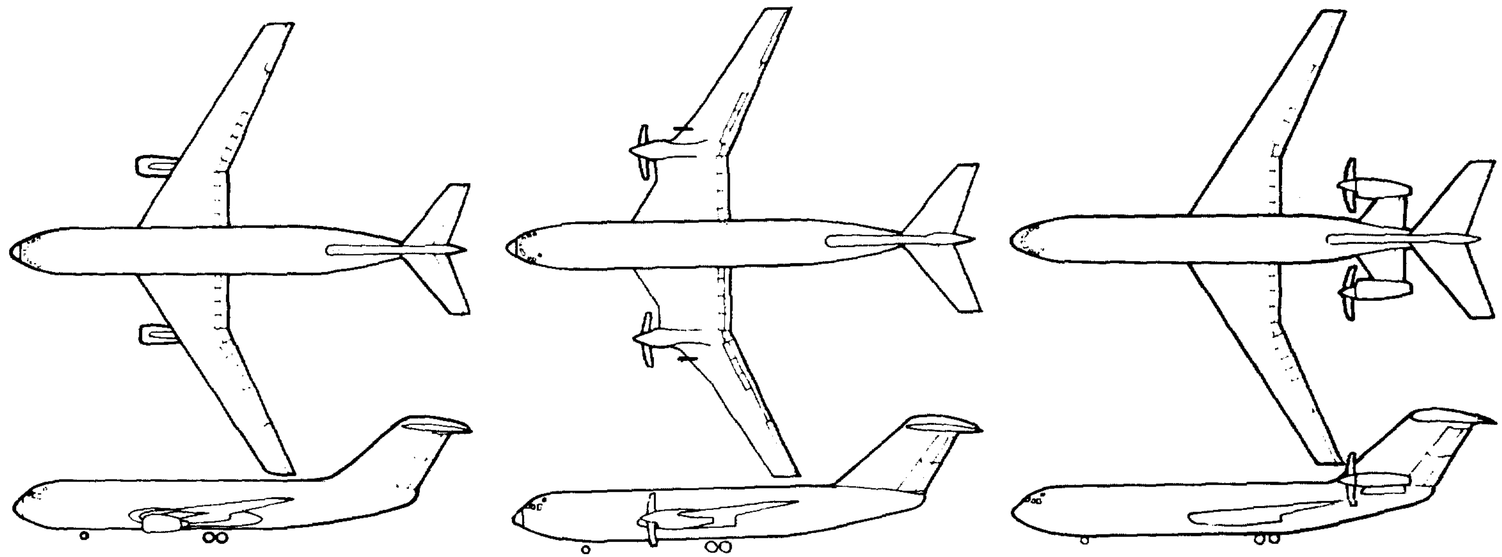
1. A turbofan powered airplane to serve as a basis for comparison
2. A prop-fan airplane with engines mounted on the wings
3. A prop-fan airplane with engines mounted on struts extending from the aft body

Figure 1 shows the three airplanes and lists their major characteristics. Current airframe technology and core engines based on the technology corresponding to certification in the 1980-1985 time period were assumed. Hamilton Standard's estimated propulsive efficiency, propeller and gearbox weights, and prices were used for all analyses.

In this study, at Mach 0.8 cruise, the installed thrust specific fuel consumption (TSFC) of the prop-fan (including allowances for reduction gearing) is 0.546 lb of fuel per hr per lb of thrust (0.0155 kg/kN-sec), versus 0.666 for the turbofan. In the absence of compensating penalties, this 18% advantage in cruise TSFC would result in a net fuel saving approaching 25%, through reduction of the airplane size needed to do the mission. However, both the weight and the drag of the prop-fan airplanes are inferior to those of the turbofan, and the resulting estimated fuel savings are reduced to 9.7% for the wing-mounted prop-fan airplane and 5.8% for the aft-mounted prop-fan.

This report (NSA CR-137938) is a summary version of the much more detailed final report (NASA CR-137937).

| | Model 767-761<br>Reference Turbofan | Model 767-762<br>Wing-Mounted Prop-Fan | Model 767-764<br>Aft-Mounted Prop-Fan |
|---|---|---|---|



| | | | |
|---|---|---|---|
| Takeoff Weight (max) | 115 350 kg (254 300 lb) | 122 060 kg (269 100 lb) | 123 970 kg (273 300 lb) |
| Operating Empty Weight | 75 050 kg (165 480 lb) | 83 710 kg (184 550 lb) | 84 690 kg (186 710 lb) |
| Wing Area | 243.2 $m^2$ (2618 $ft^2$) | 260.8 $m^2$ (2807 $ft^2$) | 242.8 $m^2$ (2613 $ft^2$) |
| Propulsion System | (2) 16 960 kg (37 400 lb)<br>SLST BPR 6 turbofans | (2) 22 722 kw (30 470 hp)<br>Engines * driving 5.98 m<br>(19.6 ft) dia prop-fans | (2) 23 110 kw (30 990 hp)<br>Engines * driving 6.03 m<br>(19.8 ft) dia prop-fans |

* Scaled STS 476 turboshafts

*Figure 1 Airplane Comparison*

## 1.2 WEIGHT

The operating empty weights of the two prop-fan aircraft are about 11.5% and 12.8% or 8660 and 9640 kg (19 070 and 21 230 lb) higher than the reference turbofan. More than half of the added weight is simply the difference between the "propulsors," i.e., between a fan and a propeller-gearbox combination. The remainder of the added weight is due to a variety of causes. One problem peculiar to the prop-fan deserves special emphasis: In cruising flight, the helical tip Mach number of the propeller blade is 1.13, so a very high noise level may be expected with much of the energy in a narrow band around the blade passing frequency. An added fuselage weight of 2670 kg (5880 lb) is required for the wing-mounted prop-fan to reduce the cabin noise to the interior levels attained by the turbofan. The arrangement having aft-mounted propellers was designed to reduce that penalty. However, for that configuration, additional structure is required to support the engine struts, very heavy skin gauges must be employed to prevent acoustic fatigue damage, and balance problems resulting from the heavy stern necessitates a bigger empennage.

## 1.3 DRAG

Both prop-fans have higher parasite drag than the turbofan. With the same high-lift devices, the wing-mounted prop-fan requires added wing area to meet the approach speed requirement because of $C_{L_{MAX}}$ penalty resulting from the placement of the nacelles on the wing leading edge. The aft-mounted prop-fan has large nacelle struts and a longer body. Both (especially the aft mount) have larger tail surfaces. A 0.012 M penalty in drag-rise Mach number was charged to the wing-mounted prop-fan because of the slipstream, which adds an average of 0.04 M to the flow velocity over 30% of the exposed wing area.



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## 1.4 FUEL ECONOMY

The block fuel of the prop-fan airplanes is shown in figure 2 as a fraction of the reference turbofan's. The net result of the combined effects of TSFC, weight, and drag is a fuel saving of 9.7% for the wing-mounted prop-fan and 5.8% for the aft-mounted prop-fan at the design range of 3333.6 km (1800 nmi). Most trips flown by airplanes of this design range are at stage lengths between 926 and 1852 km (500 to 1000 nmi). The prop-fans save somewhat more at such ranges because a greater proportion of the flight is spent in climb and maneuver, where the speed is lower than Mach 0.8 and the prop-fan's efficiency advantage is even greater.

## 1.5 DIRECT OPERATING COST (DOC)

Figure 3 shows the relative direct operating cost of the wing-mounted prop-fan and the turbofan at Air Transport Association (ATA) ranges of 966 and 1850 km (600 and 1150 statute miles) for fuel prices from 3.96¢ to 15.85¢ per liter (15¢ to 60¢ per gal.) in 1973 money. Hamilton Standard's estimates of propeller and gearbox maintenance costs were used to compute the DOC data shown. Those maintenance costs take credit for advanced design features providing better modularity and increased mean time between failures of components, and are only about 15% of the current experience maintenance costs on the propellers and gearboxes of airplanes like the Lockheed Electra.

The prop-fan fuel economy is offset by higher first cost and maintenance to the degree that little net advantage results at the 3.96¢ per liter (15¢/gal.) level prevalent before the 1973 oil embargo. At today's prices it offers a modest gain in DOC, and if world conditions should cause another jump in fuel costs, the gain could be greater.

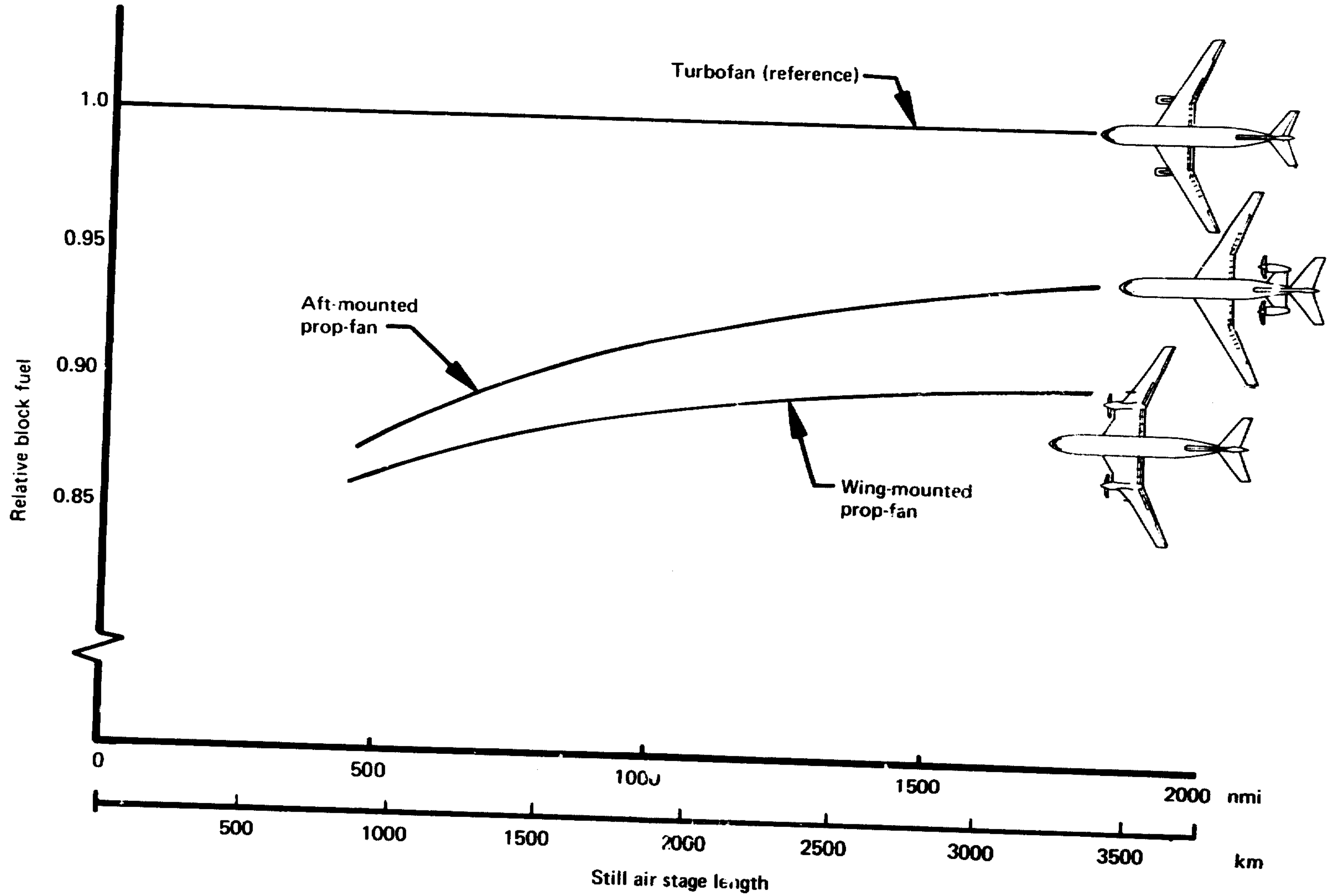


*Figure 2 Block Fuel Comparison; Mach 0.8 Cruise, 180 Passengers*

Figure 4 shows the effect of applying current turboprop maintenance cost experience on old technology turboprop aircraft to the prop-fan for the 1850 km (1150 statute mile) ATA trip. The DOC breakeven fuel price is increased to more than 7.93¢ per liter (30¢/gal.) and the economic benefit due to fuel saving disappears. Measures planned to reduce prop-fan maintenance costs are therefore of central importance to the concept.

## 1.6 UNCERTAINTIES

### 1.6.1 DRAG

The interference drag penalty resulting from the interaction between the slipstream of a heavily loaded propeller (such as the prop-fan) and a sweptback wing at a high subsonic Mach number is not well understood. The issue cannot be resolved by available test data.

In the present study, the drag-rise Mach number ($M_{DR}$) of the wing-mounted prop-fan was estimated by an area-weighted average of the $M_{DR}$'s of the immersed and unimmersed portions of the wing. This approach is convenient and gives a plausible result, but on the basis of present knowledge the correction so calculated could easily be in error by 100% in either direction.

### 1.6.2 BODY WEIGHT

According to Hamilton Standard the 30° sweepback of the prop-fan blade tip, together with its 2% thick supercritical airfoil section, will result in a noise level 10 dB lower than the value used in this study. An independent calculation treating the noise radiated by the supersonic tip as a series of little sonic booms, using an approximation found satisfactory in Boeing supersonic transport studies, gives a level near the higher value. The issue must be resolved by future tests.

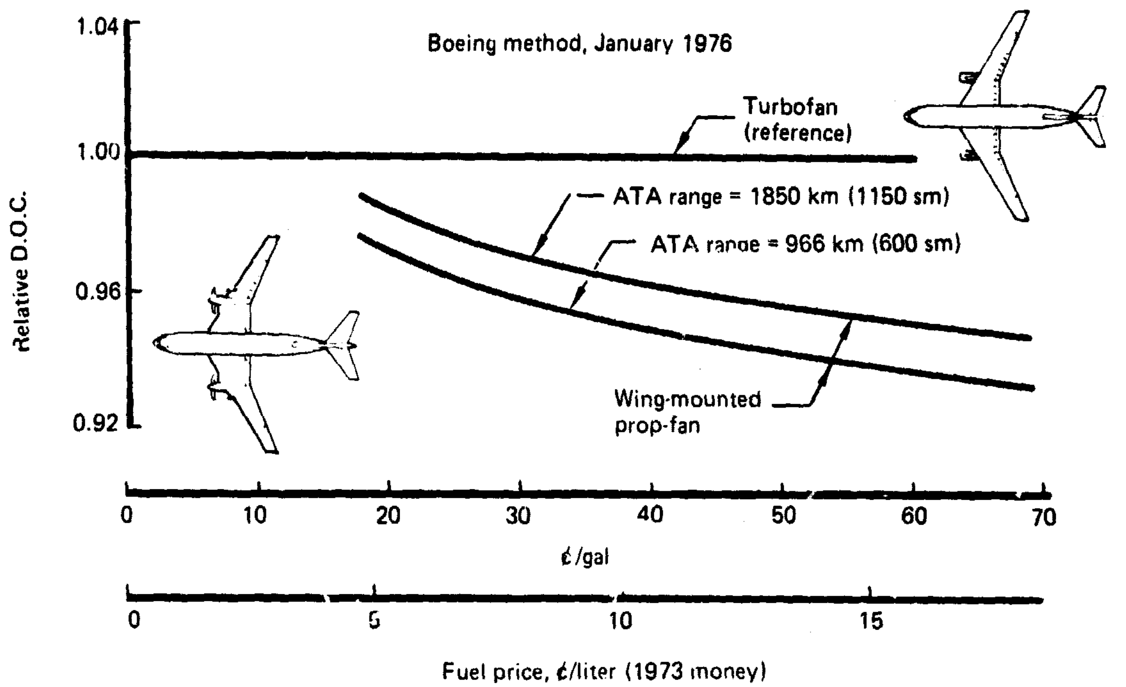


*Figure 3 Direct Operating Cost Comparison, Wing-Mounted Prop-Fan and Turbofan*

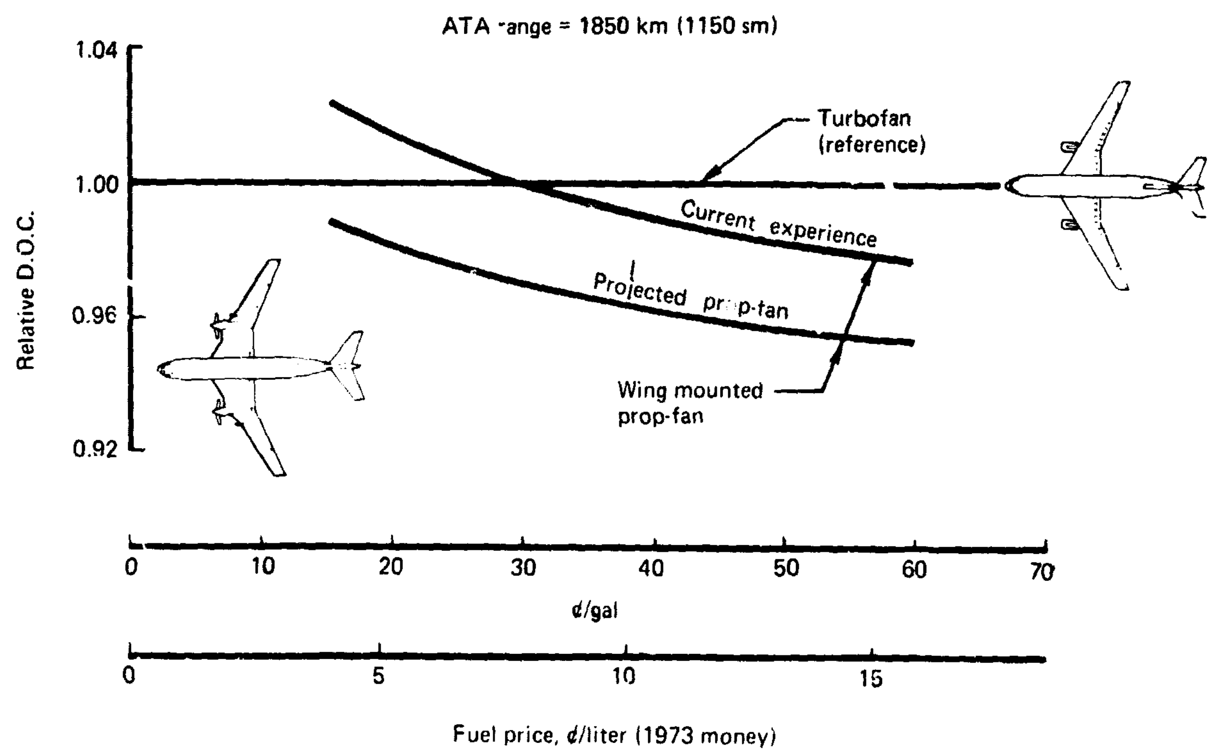


*Figure 4 Effect of Propeller and Gearbox Maintenance Cost on Direct Operating Cost*

The weight of body structural changes designed to attenuate propeller noise is also uncertain. The blade-passing frequency, around 100 Hz, is too low for effective absorption by conventional fiberglass insulation, and reliance on mass effects (heavy walls) alone would be prohibitively heavy. The approach assumed here is the use of tuned-panel structure with integral damping.

Accurate weight determination using this new method would require more effort than could be spent on this subject during this study. Also, the relation between weight and noise attenuation for this scheme is not linear, and a noise level on the high side would result in a rapidly increasing penalty. The 2670 kg (5880 lb) allowance for noise reduction is therefore subject to a double uncertainty. If the weight estimating method is correct, but the actual noise level is the lower value, the allowance would be reduced to 900 kg (1984 lb).

### 1.6.3 FUEL SAVING

The 0.012 $M_{DR}$ penalty charged to wing-slipstream interference on the wing-mounted prop-fan is worth 2.7% in block fuel at the design range, while the 2670 kg (5800 lb) for fuselage noise reduction costs another 3.6%. Together, these effects imply an uncertainty equal to about half the estimated fuel saving, in either direction.

### 1.6.4 DIRECT OPERATING COST

The effect of the drag and weight uncertainties on the estimated DOC is also substantial, equaling plus or minus one-half of the estimated 3% reduction at 30¢/gal. for an 1850 km (1150 statute mile) trip.



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## 1.7 CONCLUSIONS

The results of this study indicate the following:

- The twin prop-fan airplane offers a fuel saving of about 10% over the twin turbofan airplane for the study mission.

- For this size airplane and this mission, mounting prop-fans on the aft body of the airplane causes balance problems that more than offset the expected savings resulting from cabin noise reduction.

- Uncertainties regarding slipstream drag effects at high Mach number, the noise radiated by the propeller, and the weight of the consequent noise reduction features could increase or decrease the fuel saving by as much as 50%.

- The prop-fan offers a modest direct operating cost reduction at today's fuel prices, and a substantial one in the event of further major increases in the relative cost of petroleum.

- The drag and weight uncertainties are great enough to have a decisive influence on the prop-fan's economic potential.

## 1.8 RECOMMENDATIONS

A convincing evaluation of the prop-fan's economic and energy saving potentials requires further research and technology effort. In particular, the following tests should be made:

- Wing/nacelle/propeller combinations should be wind tunnel tested to establish the drag penalty and swirl recovery due to wing/slipstream interaction at high subsonic Mach numbers. Tests involving a simulated slipstream, emitted from a blowing device upstream of the wing, could be very useful because of the degree of control over slipstream velocity and swirl.

- Careful attention to tailoring the wing for local variations in angle of attack due to the slipstream may be essential to the full realization of the prop-fan's potential.

- Noise characteristics of thin, swept-tip propellers operating at supersonic tip Mach number and high advance ratio must be measured. This could be done in a wind tunnel if a facility combining the necessary speed capability and acoustic characteristics can be found or developed. Alternately, a scale model might be flight-tested on a business jet class airplane.

In support of these test programs, theoretical methods should be developed in both aerodynamics and acoustics for the analysis and design of high-speed propellers and wings in their mutual presence.

# 2.0 INTRODUCTION

## 2.1 BACKGROUND

Elementary considerations of momentum and energy lead to the conclusion that, in the absence of compensating losses, propulsive efficiency is always improved by accelerating more fluid by a smaller velocity increment. Introduction of the high bypass ratio turbofan engine stimulated a new generation of transport aircraft by using that principle to reduce fuel consumption without substantially sacrificing the simplicity, reliability, and low maintenance costs that have come to be expected by the airlines since reciprocating engines were replaced by turbojets.

The dramatic increase in the relative cost of fuel following the 1973 Arab oil embargo, along with national concern over the long-term prospect of fossil fuel depletion, have prompted government and industry to examine possibilities for further reducing aircraft fuel consumption.

A recent NASA-sponsored study (ref. 1) concluded that modest gains in efficiency could be achieved by pushing the turbofan technology further. Geared fans, very high overall pressure ratios, and even more elevated turbine inlet temperatures would be required, and engine price and maintenance costs would be expected to rise. The same study also noted that the propeller offered much more dramatic gains than advanced turbofans if it could be adapted to the Mach 0.75+ cruise speed favored by airframe technology and expected by the traveling public.

The high propulsive efficiency of propellers is hard to maintain at cruise speeds above Mach 0.7 because either:

- The helical tip Mach number becomes supersonic, and the outer section of the blade incurs drag and noise penalties, or

- The rotational speed must be reduced to the point where excessive slip-stream swirl necessitates the added weight and complexity of dual rotation.

In 1975, the Hamilton Standard Division of United Technologies Corporation proposed the pro-fan concept, in which a supersonic tip Mach number is accepted, but very thin, swept-back blade tips are used to alleviate drag and noise. To keep the diameter reasonable while absorbing the very high power required for a high-speed transport airplane, eight broad blades are used. Figure 5 shows the appearance of this "advanced technology unducted propulsor."

Hamilton Standard estimated that an installed propulsive efficiency of 79.5% at Mach 0.8 cruise could be achieved. A net reduction of 18% in TSFC over a bypass ratio 6 turbofan would then be expected. At the time of this writing, the first of a series of wind tunnel tests has been run, and attainment of the estimated efficiency appears likely.

## 2.2 STUDY GROUND RULES

Twin engine airplanes designed to carry 180 to 200 passengers in a 10% first/90% economy class cabin configuration with 0.97/0.86 m (38/34 in.) seat pitch are the subject of this study. The mission range is 3333.6 km (1800 nmi), and the cruise speed objective is Mach 0.8. The minimum cruise altitude is 9144 m (30 000 ft) for operation above the weather and compatibility with modern air traffic control requirements. Because this airplane is a medium range design, a maximum takeoff field length of 2134 m (7000 ft) at full payload for sea level standard day conditions was specified. An additional requirement, imposed by Boeing and based on experience with commercial operators, is that the maximum sea level standard day approach speed at the design mission landing weight should be 65 m/sec (126 KEAS). This ensures that the approach speed will not exceed 70 m/sec (135 KEAS) for landings at higher weights on shorter route segments.

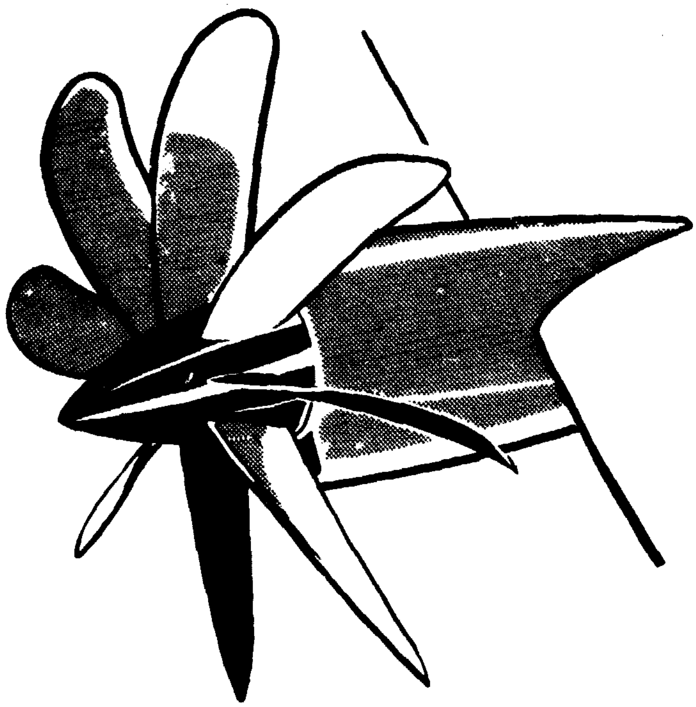

*Figure 5 Prop-Fan*

Equal cabin comfort levels were required. This implies that any extra noise generated by the propellers must be attenuated to the interior cabin level of the reference turbofan airplane by appropriate airplane/engine arrangement, structural design measures, or insulation.

Turbofan engine data were based on 1985 technology as embodied in the JTIOD technology level data base developed for a previous NASA-sponsored Boeing study (ref. 2). A turboshaft core engine of comparable technology, the Pratt & Whitney STS-476, served as the basis for prop-fan propulsion system performance.

## 2.3 PROGRAM TASKS

The tasks performed in this investigation began with the parametric design of two prop-fan airplanes and a turbofan airplane to serve as a standard of comparison. One prop-fan used a conventional arrangement having engines on the wing, while the other had them mounted on struts projecting from the aft body. (A scheme with engines mounted on the tips of the horizontal stabilizer was briefly considered and rejected because trim requirements favor a variable incidence horizontal tail.)

Because of Boeing's extensive experience in turbofan transport design, the parametric reference airplane did not require detailed examination to validate weights and performance. The newness of the prop-fan, however, demanded airplane design evaluation and iteration to ensure consistency and reasonableness. It was originally planned to select only one of the two prop-fan designs for iteration, but no clearly preferable choice was evident from the parametric study. Therefore, both were evaluated.

The remaining tasks were the determination of the sensitivity of the prop-fan airplane takeoff weight, empty weight, and fuel burned to variations in propulsion system characteristics, and comparisons of direct operating costs with those of the reference turbofan airplane.

# 3.0 DESIGN EVALUATION

## 3.1 REFERENCE TURBOFAN AIRPLANE

The reference turbofan configuration and characteristics are shown in figure 6 and table I.

## 3.2 WING-MOUNTED PROP-FAN AIRPLANE

### 3.2.1 ARRANGEMENT CONSIDERATIONS

The configuration and geometric characteristics of the prop-fan powered airplane with the wing-mounted engines are shown in figures 7 and 8, and table II.

The wing-mounted prop-fan has the same general arrangement as the turbofan airplane except for the engine installation. The spanwise location of the engine was selected to provide a blade-tip-to-body clearance of 0.8 propeller diameters, as recommended by Hamilton Standard.

The propellers have opposite rotation, upward on the inboard side. This sense of rotation is expected to give less cabin noise than the other one, and symmetry of wing tailoring is preserved.

### 3.2.2 AERODYNAMIC CHARACTERISTICS

The aerodynamic characteristics of the wing-mounted prop-fan airplane were based on those of the turbofan airplane with corrections applied to account for the "over-under" nacelle installation and the presence of the slipstream.

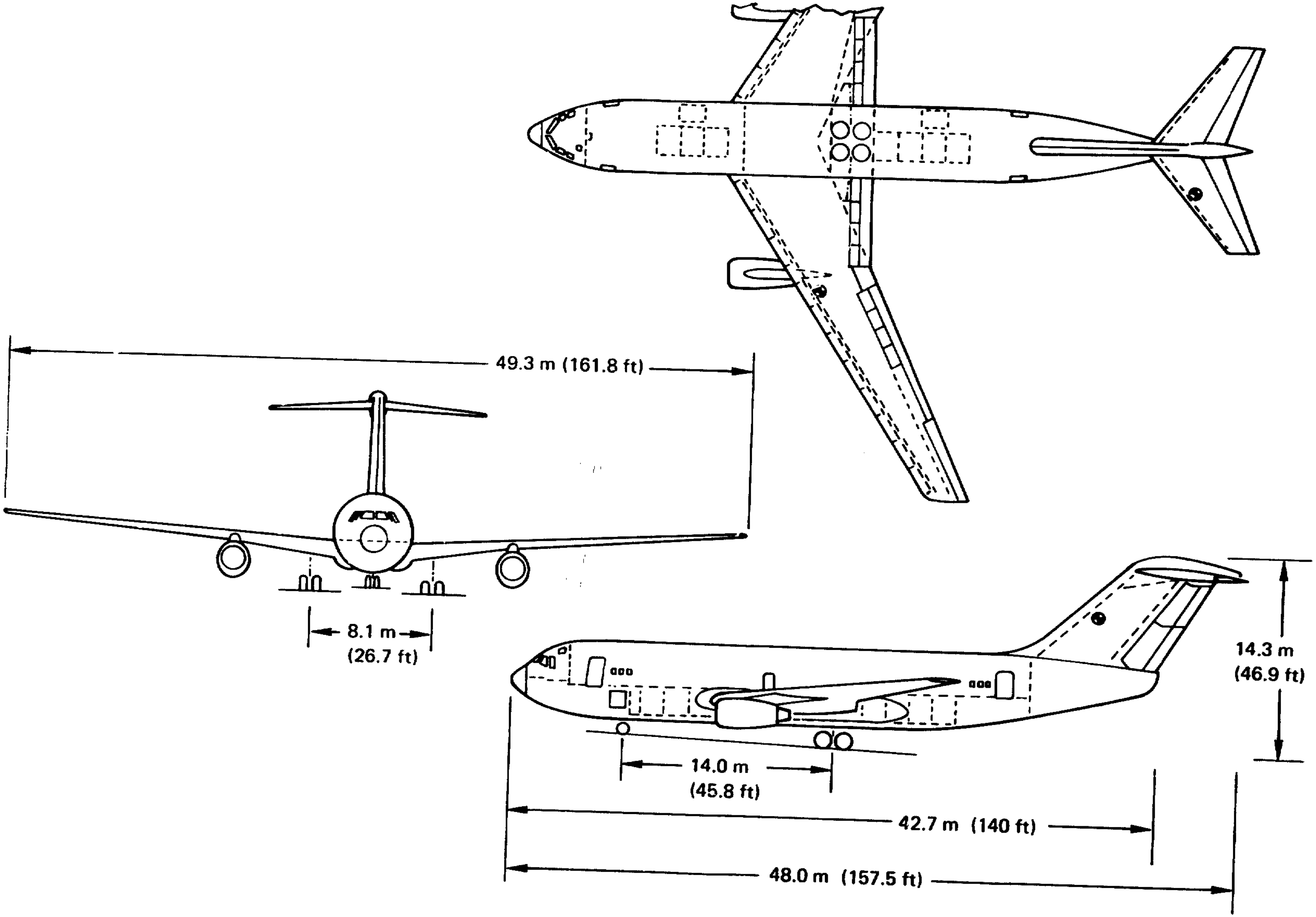


*Figure 6 General Arrangement, Turbofan*

## *Table I 767-761 Baseline Turbofan Airplane Characteristics and Performance*

| | | |
|---|---|---|
| Weights | TOGW, kg (lb) | 115 350 (254 300) |
| | OEW, kg (lb) | 75 050 (165 480) |
| | Landing weight (mission), kg (lb) | 98 340 (216 800) |
| | (maximum), kg (lb) | 104 490 (230 370) |
| | Payload, pass./kg (pass./lb) | 180/16 738 (180/36 900) |
| | Maximum fuel capacity (kg (lb) | 68 668 (151 388) |
| | C.G. limits, % MAC | 15 fwd, 43 aft |
| | T/W | .235 |
| | W/S, $N/m^2$ ($lb/ft^2$) | 4649.2 (97.1) |
| Performance | Still air range, km (nmi) | 3333.6 (1800) |
| | Cruise Mach number | 0.80 |
| | Cruise altitude, m (ft) | 11 890 (39 000) |
| | Range factor, km (nmi) | 23 240 (12 550) |
| | L/D average cruise | 18.21 |
| | SFC, kg/kN-sec (lb/hr/lb) | 0.01886 (0.666) |
| | TOFL, m (ft) | 2134 (7000) |
| | C.G. position, % MAC | 15 |
| | $V_{APP}$, m/sec (KEAS) | 63 (122) |
| | Block fuel, kg (lb) | 17 218 (37 960) |
| | Reserves, kg (lb) | 6550 (14 450) |
| | Total fuel, kg (lb) | 23 990 (52 890) |
| | Block fuel, kg/pass. km (lb/pass. nmi) | 0.0287 (0 117) |
| Power plants | Number | 2 |
| | Bypass ratio | 6 |
| | SLS thrust/engine uninstalled | 166 000 N (37 400 lb) |
| Body | Length, m (in.) | 42.67 (1680) |
| | Maximum diameter, m (in.) | 5.38 (211.6) |
| | Accommodations | 180 passengers–10% 1st, 90% tourist<br>8 LD-3 containers, 35.79 $m^3$ (1264 $ft^3$) |
| Landing gear m (in.) | Nose | (2)-0.86x0.28 (34x11) |
| | Main | (8)-1.09x0.42 (43x16.5) |
| | Truck size | 1.32x0.97 (52x38) |
| | Oleo stroke (extended to static) | 0.51 (20) |

| | | Wing | Horizontal tail | Vertical tail |
|---|---|---|---|---|
| Wing and empennage | Area, $m^2$ ($ft^2$) | 243.2 (2618) | 50.3 (541.4) | 50.0 (537.9) |
| | Aspect ratio | 10 | 4.0 | 0.8 |
| | Taper ratio | 0.353 | 0.4 | 0.65 |
| | c/4 sweep, deg | 30 | 35 | 45 |
| | Incidence, deg | [1] | variable | 0 |
| | Dihedral, deg | 5 | -3 | – |
| | t/c, % | [2] | 10.5 | 12 |
| | MAC, m (in.) | 5.308 (208.963) | 3.763 (148.157) | 8.022 (315.830) |
| | Span, m (in.) | 49.317 (1941.628) | 14.184 (558.438) | 6.323 (248.930) |
| | Tail arm, m (in.) | – | 24.767 (975) | 19.202 (756) |
| | Tail vol coefficient | – | 0.965 | 0.080 |

[1] Wing incidence: SOB 3.75
MAC 2.00
TIP -1.00

[2] Wing t/c, %: SOB - 13.1 (total chord)
BL 387 - 10.5 (const outboard)

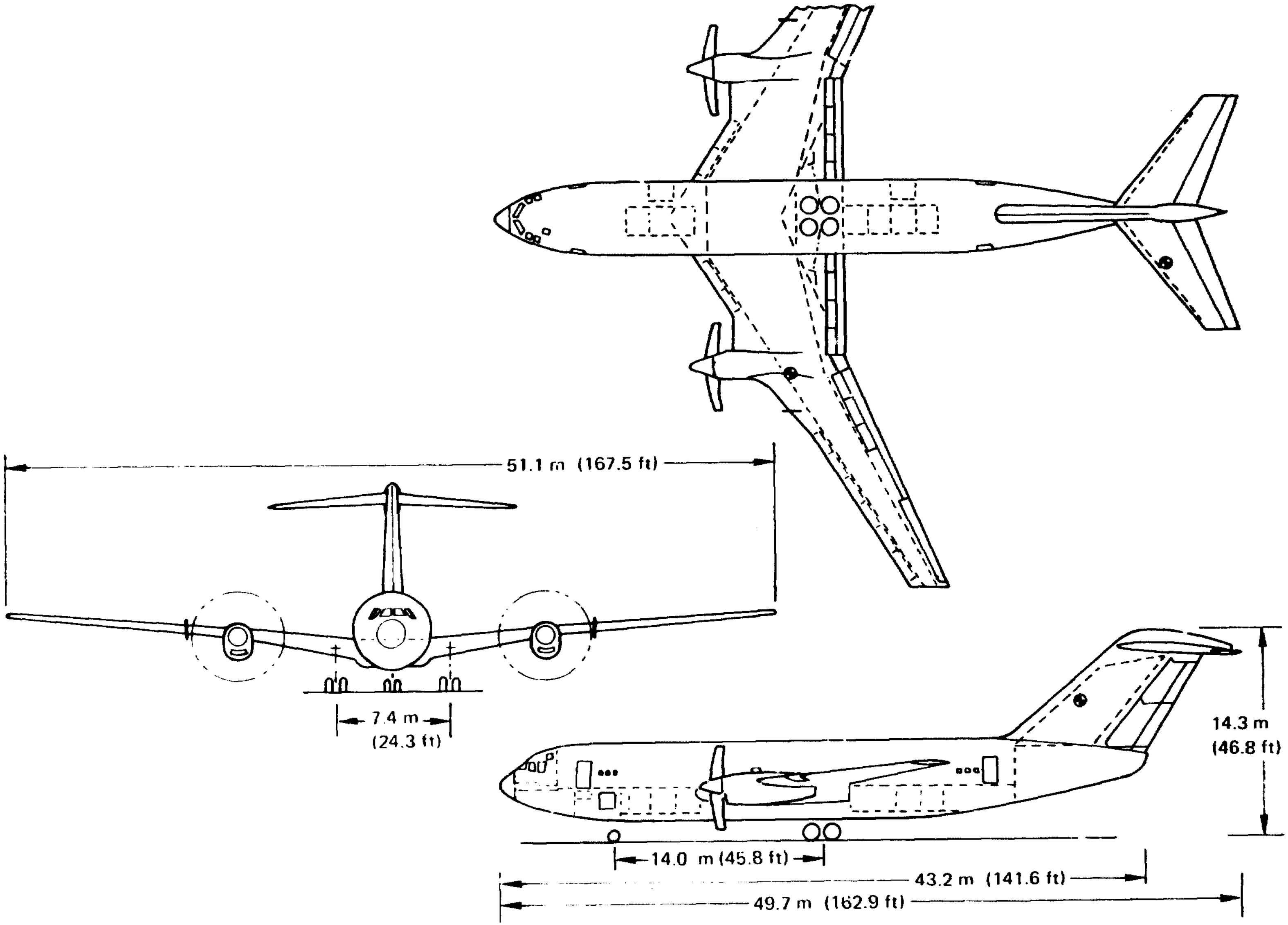


*Figure 7 General Arrangement, Wing-Mounted Prop-Fan (767-762)*

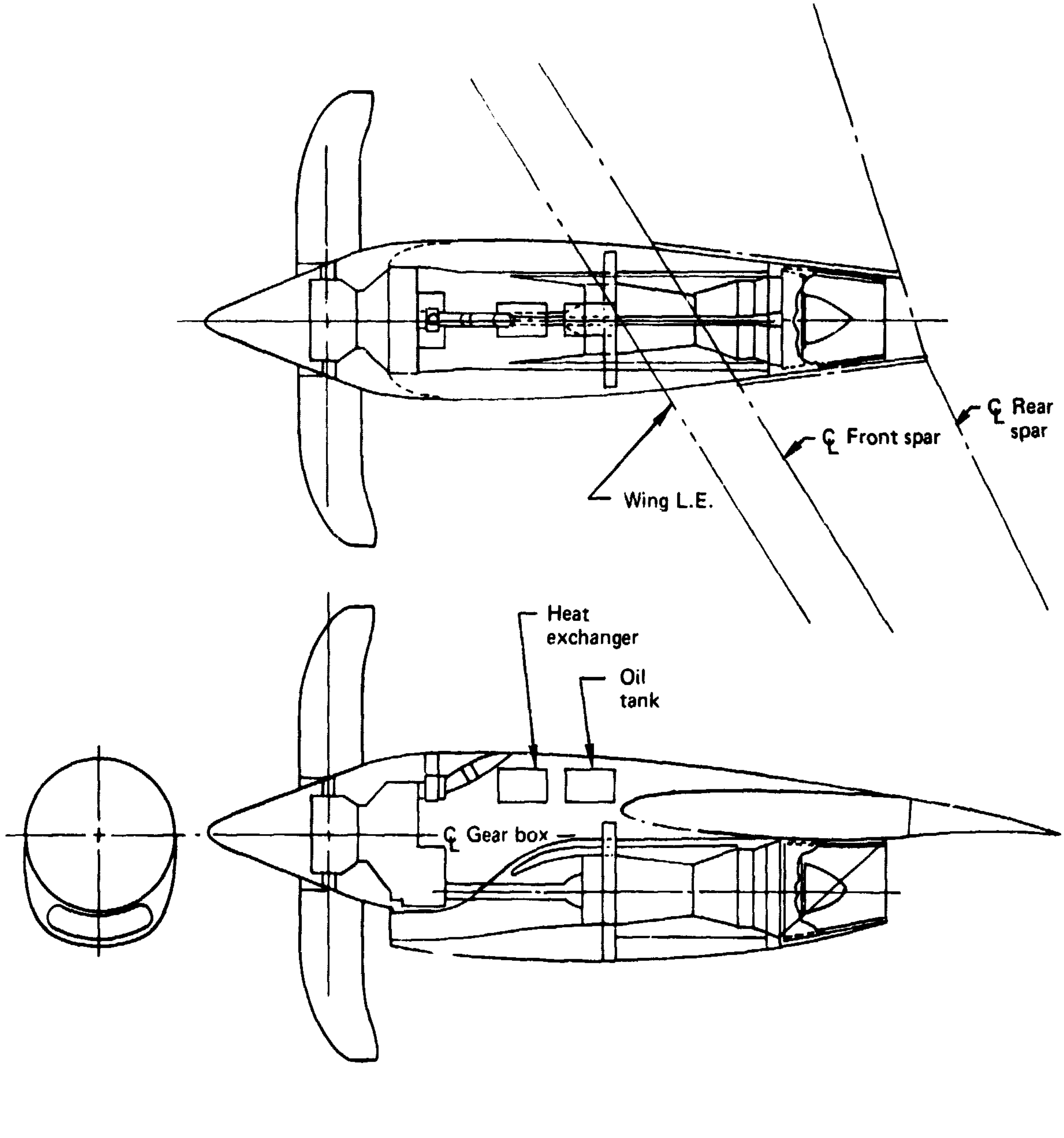


*Figure 8 Prop-Fan Installation*

*Table II 767-762 Wing-Mounted Prop-Fan Airplane Characteristics and Performance*

| | | |
|---|---|---|
| Weights | TOGW, kg (lb) | 122 060 (269 100) |
| | OEW, kg (lb) | 83 710 (184 550) |
| | Landing weight (mission, kg (lb) | 116 685 (235 200) |
| | (maximum), kg (lb) | 110 580 (243 780) |
| | Payload, pass./kg (pass./lb) | 180/16 738 (180/36 900) |
| | Maximum fuel capacity, kg (lb) | 69 592 (153 423) |
| | C.G. limits, % MAC | 8 fwd, 34 aft |
| | T/W equivalent | .279 |
| | W/S, N/m$^2$ (lb/ft$^2$) | 4592 (95.9) |
| Performance | Still air range, km (nmi) | 3333.6 (1800) |
| | Cruise Mach number | 0.80 |
| | Cruise altitude, m (ft) | 11 280 (37 000) |
| | Range factor, km (mni) | 26 780 (14 460) |
| | L/D average cruise | 17.20 |
| | SFC, kg/kN·sec (lb/hr/lb) | 0.0155 (0.546) |
| | TOFL, m (ft) | 1476 (4841) |
| | C.G. position, % MAC | 8 |
| | $V_{APP}$, m/sec (KEAS) | 65 (126) |
| | Block fuel, kg (lb) | 15 550 (34 280) |
| | Reserves, kg (lb) | 6250 (13 780) |
| | Total fuel, kg (lb) | 22 060 (48 630) |
| | Block fuel, kg/pass. km (lb/pass. nmi) | 0.02596 (0.106) |
| power plants | Number | 2 |
| | Type | Scaled P & W STS476 |
| | Power | 22 722 kW (30 470 SHP) |
| Landing gear, m (in.) | Nose | (2)–0.86 x 0.28 (34 x 11) |
| | Main | (8)–1.09 x 0.42 (43 x 16.5) |
| | Truck size | 1.32 x 0.97 (52 x 38) |
| | Oleo stroke (extended to static) | 0.51 (20) |
| Body | Length, m (in.) | 43.15 (1699) |
| | Maximum diameter, m (in.) | 5.38 (211.6) |
| | Accommodations | 180 passengers–10% 1st, 90% tourist<br>8 LD-3 containers, 35.79 m$^3$ (1264 ft$^3$) |

| Wing and empennage | | Wing | Horizontal tail | Vertical tail |
|---|---|---|---|---|
| | Area, m$^2$ (ft$^2$) | 260.8 (2807) | 64.3 (692) | 55.1 (593) |
| | Aspect ratio | 10 | 4.0 | 0.8 |
| | Taper ratio | 0.353 | 0.4 | 0.65 |
| | c/4 sweep, deg | 30 | 35 | 45 |
| | Incidence, deg | [1] | – | – |
| | Dihedral, deg | [2] | -3 | -- |
| | t/c, % | [3] | 10.5 | 12 |
| | MAC, m (in.) | 5.496 (216.37) | 4.254 (167.49) | 8.425 (331.71) |
| | Span, m (in.) | 51.066 (2010.49) | 16.036 (631.32) | 6.641 (261.45) |
| | Tail arm, m (in.) | – | 25.171 (990.98) | 19.327 (760.90) |
| | Tail vol coefficient | – | 1.129 | 0.080 |

[1] Wing incidence: SOB 3.75°
MAC 2.00°
TIP 1.00°

[2] Wing dihedral: Inboard 7.5°
BL 402.1 --4.3° outboard

[3] Wing t/c%: SOB--13.1 (total chord)
BL 427–10.5
(const outboard)



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### 3.2.3 HIGH-SPEED CHARACTERISTICS

Because of the many uncertainties in predicting slipstream effects in high-speed compressible flow, a simplified approach was adopted to estimate the cruise-drag polars for the wing-mounted prop-fan.

The portion of wing immersed in the slipstream experiences an effective Mach number in excess of freestream. Because immersed surfaces also experience an elevated slipstream dynamic pressure, a scrubbing drag correction was applied to the immersed portions of wing and nacelles. At Mach 0.8 cruise, this amounted to a drag coefficient increment of 0.0003.

The over-under nacelle installation also gives rise to a degradation in high-speed drag characteristics, even when careful aerodynamic tailoring is employed. This takes the form of an increase in configuration profile drag due to lift (polar shape). The penalty applied, based on Boeing test results for over-under nacelle installations, increased with lift coefficient and amounts to a 0.0008 drag coefficient increment at a lift coefficient of 0.5.

The resulting total parasite drag coefficient at Mach 0.7 and 11 280 m (37 000 ft) altitude is 0.0166, and maximum lift-to-drag ratio at Mach 0.8 is 17.4.

No credit was taken for the potentially favorable thrust forces resulting from wing-induced slipstream derotation (section 3.2.4). Analysis of applicable experimental data indicates that the effect is probably small, and other compensating unfavorable drag phenomena could arise because of local loading effects.

### 3.2.4 SLIPSTREAM CHARACTERISTICS AND POWER EFFECTS

Maximum slipstream swirl angles vary from $6^{o}$ during cruise to over $20^{o}$ at takeoff. Maximum axial velocity increments in the fully-contracted slipstream can be expected to be as much as 10% of freestream velocity in cruise and 75% of freestream at takeoff.

The large swirl velocities in the slipstream imply that a considerable portion of the power input is not converted into thrust. This effective thrust loss increased with propeller power loading (decreasing ideal efficiency). For the power-loadings considered in this study, it amounts to about 8% in cruise and 13% at takeoff.

A considerable increase in propulsive efficiency could be achieved if the slipstream swirl energy were recovered. Dual rotation propellers achieve this result directly, at considerable cost in weight and mechanical complexity. Stators mounted on the nacelle have been proposed as a simpler alternative.

The wing itself may be considered a very large chord stator, and can be expected to develop some thrust from derotating the slipstream, compensating for the problems discussed above to an unknown extent.

Results of a preliminary vortex-lattice analysis of a swept wing immersed in a swirling slipstream are summarized in figure 9. Thrust coefficient and slipstream characteristics correspond to prop-fan cruise conditions. The axial force results tabulated in the figure indicate that about 50% of the swirl thrust loss is potentially recoverable (in shock- and separation-free flow), equivalent to an increase of about 4% in propeller efficiency. The problem of swirl thrust recovery is complex and subject to practical constraints on achievable local loadings. Wind tunnel testing will be required for drag validation. Therefore, no performance credit for the thrust recovery was taken in this study.

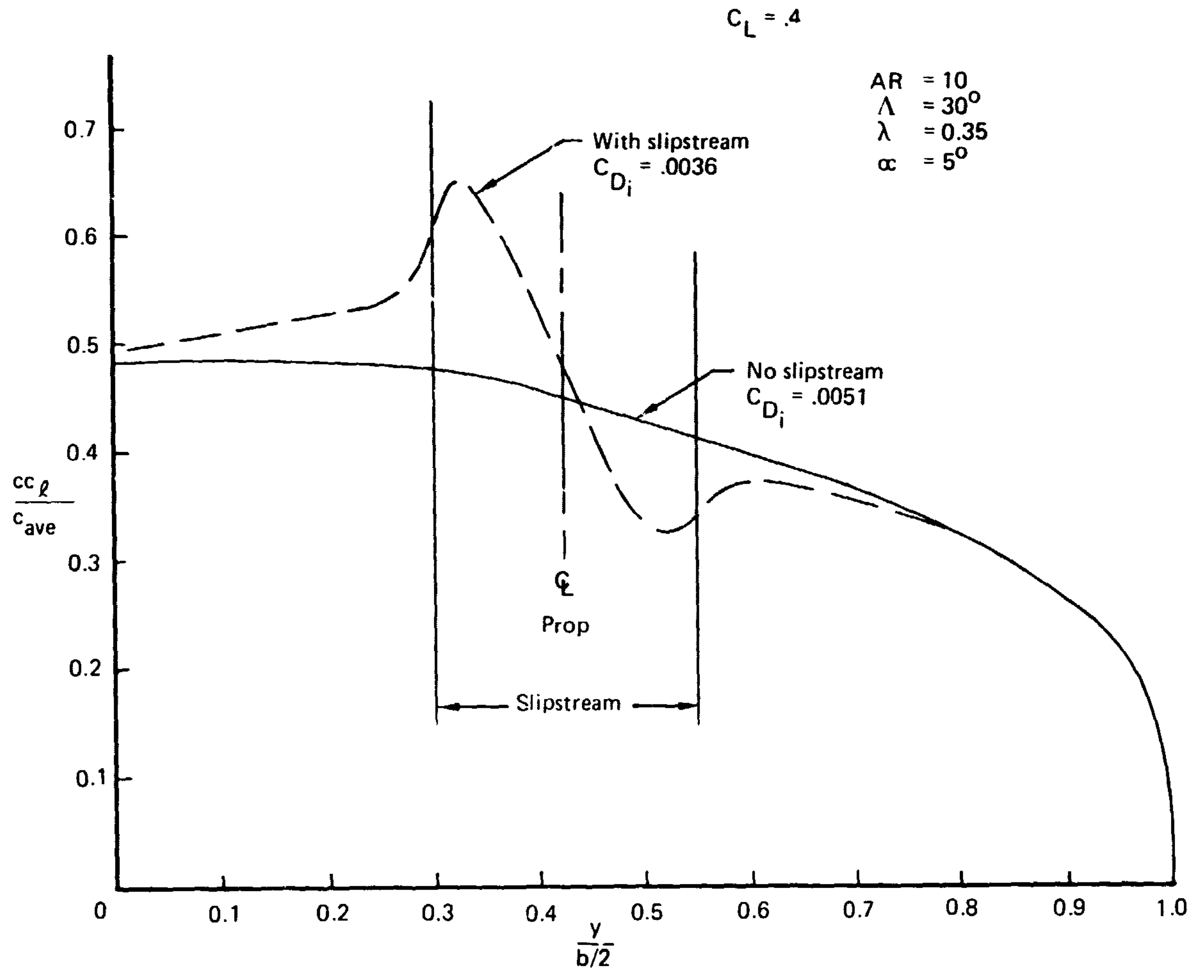


*Figure 9 Effect of Slipstream on Span Load Distribution*

The slipstream magnifies aerodynamic forces on immersed surfaces by virtue of its increased dynamic pressure. For cases in which the propeller is at an effective angle of attack, a rotation of these forces due to the deflection of the slipstream away from the freestream direction occurs. Resolved propeller thrust and normal forces must be taken into account.

At small propeller angles of attack, the largest drag component is simply the magnified scrubbing drag force. At negative propeller angles of attack, forward rotation of the lift vector produces an effective thrust; at positive angles of attack, the same force is rotated aft, giving rise to an appreciable drag component. At large positive propeller angles, both the propeller normal force and the reduction in resolved thrust add to the drag.

At most usable angles of attack, the increased lift forces outweigh the added drag, giving an increase in L/D due to power. However, in the engine-out condition, appreciable yawing and rolling moments must be trimmed, causing a large increase in drag, generally outweighing any beneficial power effects.

In addition, sizing of trimming control surfaces such as vertical fin, rudder and ailerons may be dictated by these engine-out moments, leading to further increases in drag and weight.

Accurate determinations of propeller thrust variations, normal force, and slipstream deflection with angle of attack and power are of crucial importance in any power effects calculation or analytical flow modeling work. Exploration of slipstream characteristics should therefore command equal priority to the determination of direct propeller forces in any future wind tunnel testing of the prop-fan.

### 3.2.5 "OVER-UNDER" NACELLE INSTALLATIONS

Even in the absence of slipstream effects, the presence of an over-under nacelle, such as that of the wing-mounted prop-fan airplane, can degrade the lift and drag characteristics of a swept wing. Vortices spring from the wing leading-edge-nacelle juncture areas and flow back over the wing. These vortices constrain the flow in a manner similar to a "fence," an effect particularly noticeable in the boundary layer flow over the aft region of the upper surface. Wind tunnel oil-flow visualization pictures typically show regions of low energy or separated flow near the wing trailing edge and adjacent to the two well-defined vortices, while force measurements show a reduction in lift and an increase in drag compared to corresponding clean-wing data. These phenomena are observed over the whole range of speed and are present even when careful aerodynamic tailoring is employed. Because the vortex strengths increase with angle of attack and hence, with lift coefficient, the drag penalty is felt as a degradation in drag due to lift.

In the high-lift configuration, the over-under nacelle can cause an appreciable reduction in maximum lift, as well as a drag increase.

### 3.2.6 NACELLE INTEGRATION CONCEPTS

A successfully integrated wing-mounted prop-fan nacelle design will probably embody some concepts shown in figure 10. The inboard leading-edge "crank" was developed in Boeing low-speed wind tunnel tests as a practical remedy for the maximum lift penalty associated with the over-under nacelle. The crank makes the angle of the notch between the wing leading edge and the nacelle sidewall less acute, reducing the severity of the inboard vortex. Leading-edge device effectiveness also is improved.

The cranked leading-edge extension, together with a swept leading-edge fillet outboard of the nacelles, also will permit incorporation of local

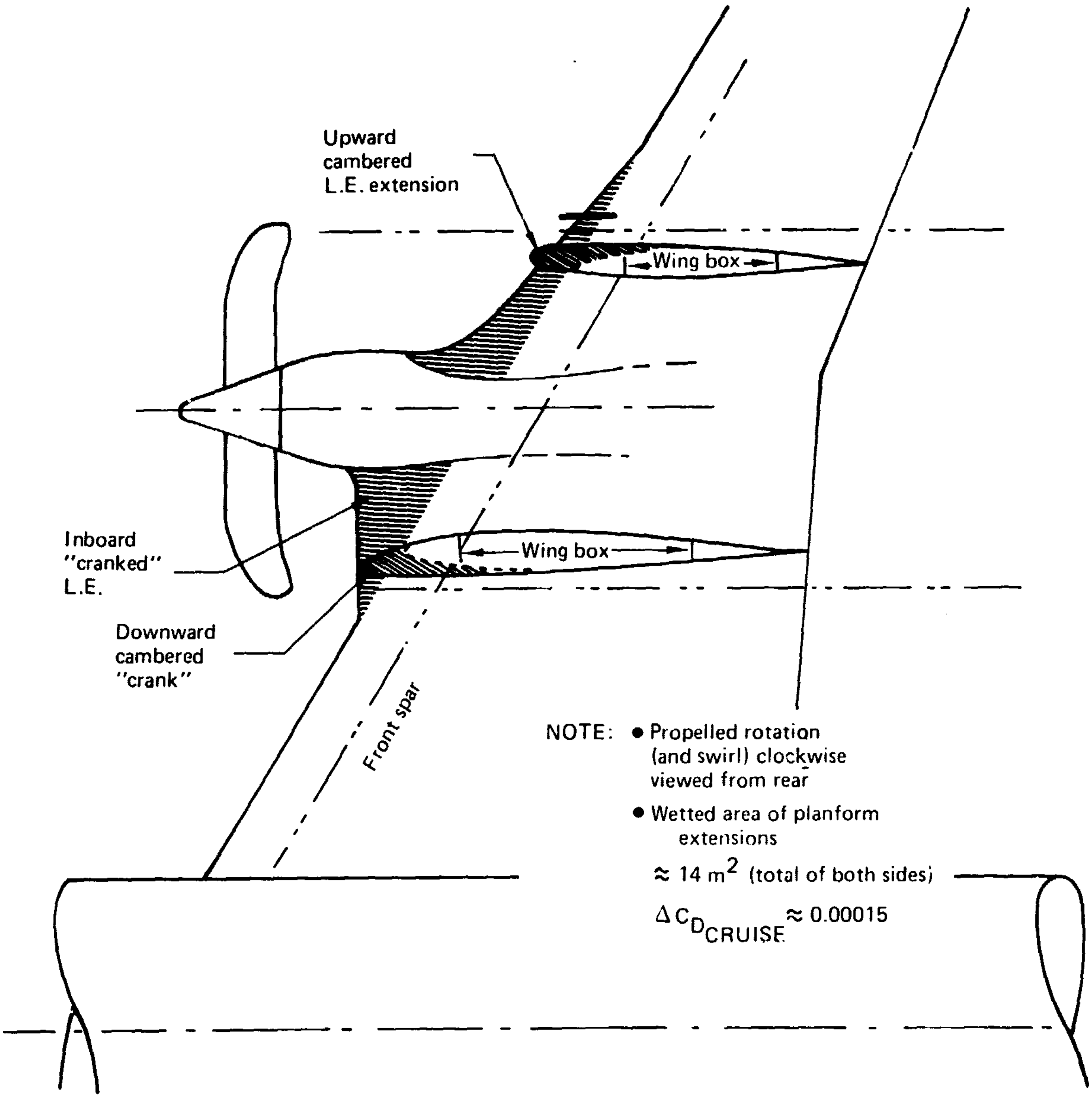


*Figure 10 Prop-Fan Wing Nacelle Intregration*

leading-edge camber without distorting the wing structural box. This leading-edge camber will be required to prevent excessive front loading of the wing sections in the swirling slipstream. A drooped leading edge will be used on the upcoming blade side, where the swirl produces a positive effective angle-of-attack increment. Some negative camber will be desirable outboard of the nacelle.

### 3.2.7 LEADING-EDGE DEVICES

Leading-edge devices will be required over the whole exposed span to provide power-off maximum lift comparable to that of turbofan airplanes. With power on, these devices must not produce excessive drag in the high-energy slipstream.

Figure 11 shows a possible leading-edge arrangement near the nacelle. On the inboard side a large-chord sealed slat is proposed, which will be deployed in both power-on and power-off conditions. The slat will be designed for minimum drag power-on and will be suitably aligned with the local swirling slipstream flow ($\Delta\alpha_{swirl} \approx 20^{o}$), but also will provide adequate leading-edge protection under power-off conditions.

Outboard of the nacelle, where the swirl is downward, a leading-edge device would probably cause too much drag. It is expected that leading edge camber alone will suffice for the power-on condition, but power-off stall protection will require a high-performance device like a curved Kruger flap. To take full advantage of the wing's potential minimum speed performance, this flap would probably have to be extended automatically, under the control of an engine torque sensing system.

### 3.2.8 CABIN ACOUSTIC ENVIRONMENT

The external noise level from which the cabin interior must be isolated is much more severe on the prop-fan airplane than on the reference turbofan because of the propeller.

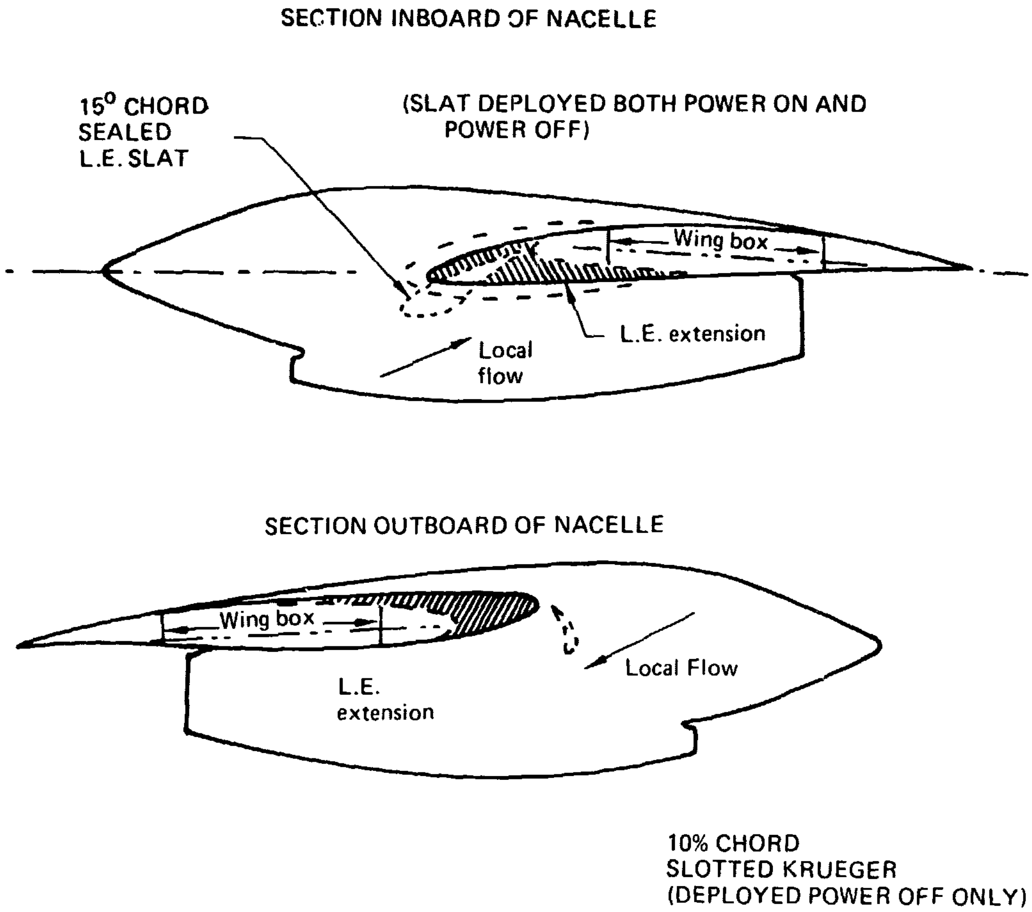


*Figure 11 Prop-Fan Leading Edge Device Integration*

Figure 12 shows a comparison of interior overall sound pressure levels (OASPL). The upper line shows the level that would prevail in the prop-fan if cabin structure and noise treatment were the same as the turbofan's. Shading indicates attenuation required to provide equal comfort levels in the two airplanes. Equal OASPLs were not required on a seat-by-seat basis, but rather the turbofan noise curve was shifted so that the location of highest noise in the turbofan corresponded to the highest prop-fan noise location. Shading on the figure is coded to indicate the noise attenuation measures required.

The weight of the additional propfan airplane noise treatment features indicated on figure 12 is estimated to be 2670 kg (5880 lb). However, the tuned-structure-with-damping noise attenuation technology is new, and the associated weights are subject to considerable uncertainty, as indicated by the dot-shaded area in figure 13. For 25 dB of attenuation (Boeing estimated requirement), this weight might be as low as 1450 kg (3200 lb) or as high as 4550 kg (10 000 lb). For 15 dB of attenuation (Hamilton Standard estimated requirement), the range of uncertainty is reduced considerably, to 700 to 1100 kg (1540 to 2420 lb).

### 3.3 AFT-MOUNTED PROP-FAN AIRPLANE

The model 767-764 aft-mounted prop-fan configuration and characteristics are shown in figure 14 and table III. The purpose of mounting the engines on the aft body was to reduce the weight penalty for cabin noise control by placing the propellers behind the aft pressure bulkhead. This benefit was partly offset by the weight required to make the aft body structure resistant to sonic fatigue damage from the propeller noise.

The OEW c.g. is moved aft in comparison to the model 767-762. Therefore, the payload c.g. and OEW c.g. no longer coincide, requiring a design for a wider c.g. operating range. In addition, the tail arm was reduced,

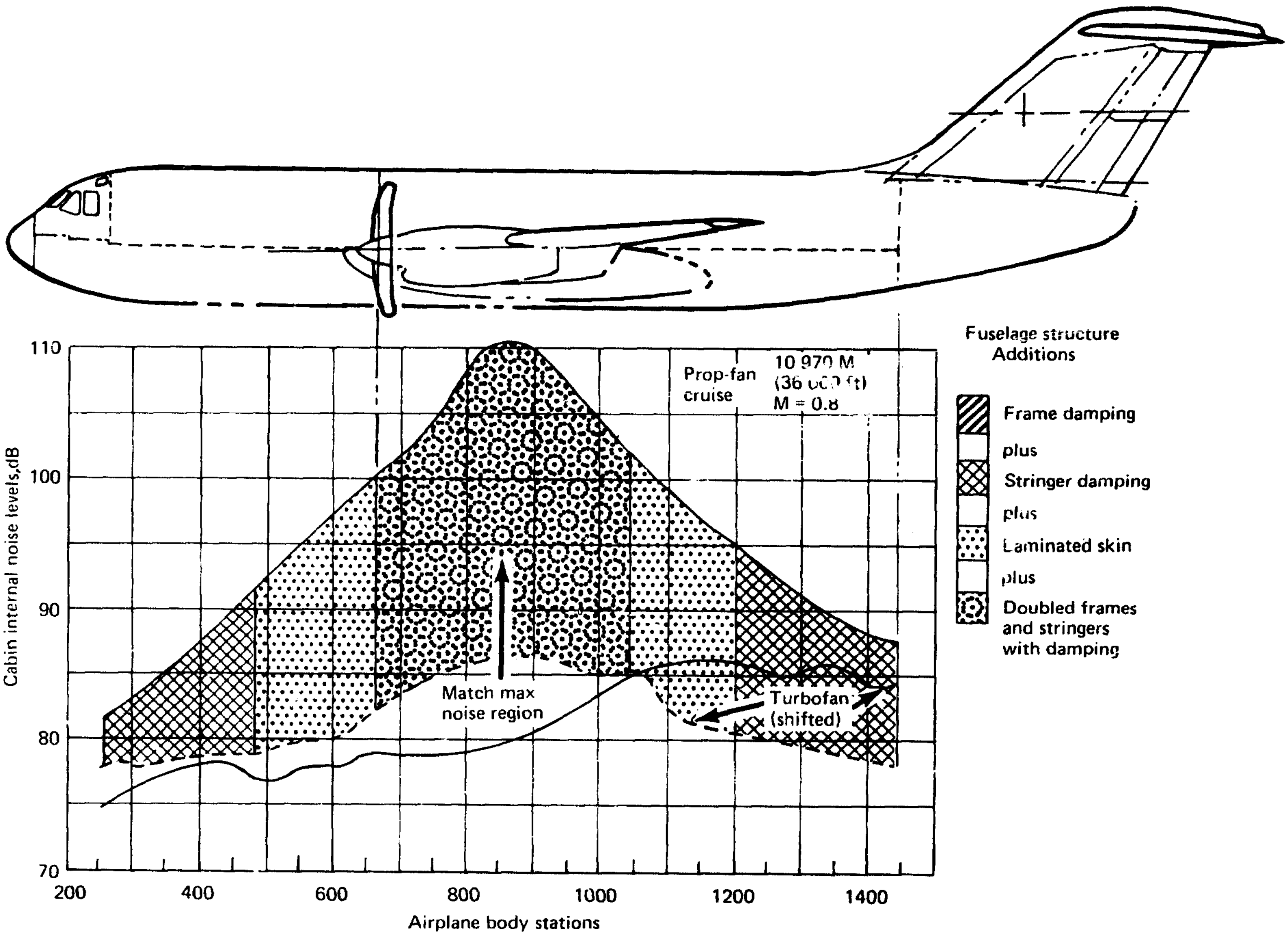


*Figure 12 Prop-Fan 767-762 Fuselage Noise Reduction Requirements
Peak Cabin Noise Region Comparable to Turbofan Peak Region*

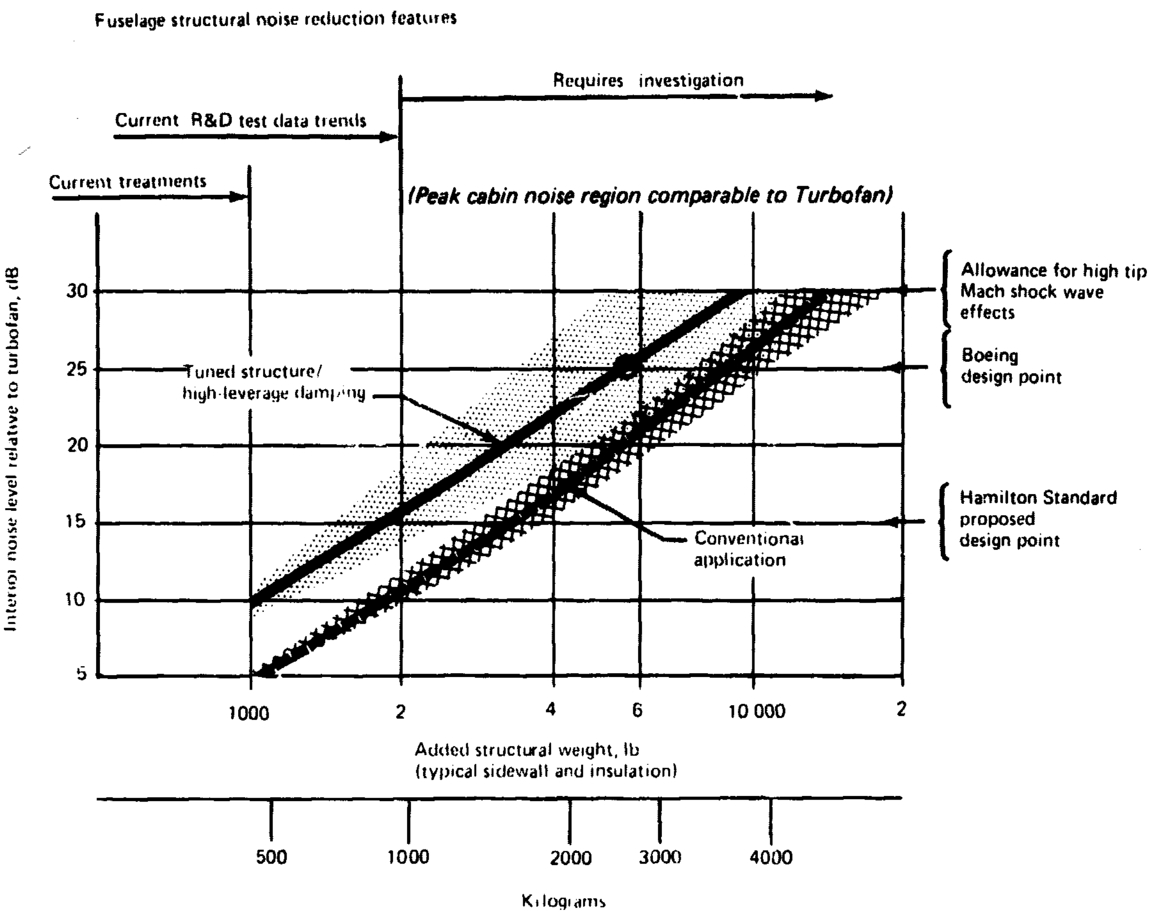


*Figure 13 Weight Trends of Wing-Mounted Propeller for Cruise Interior Noise Requirements*

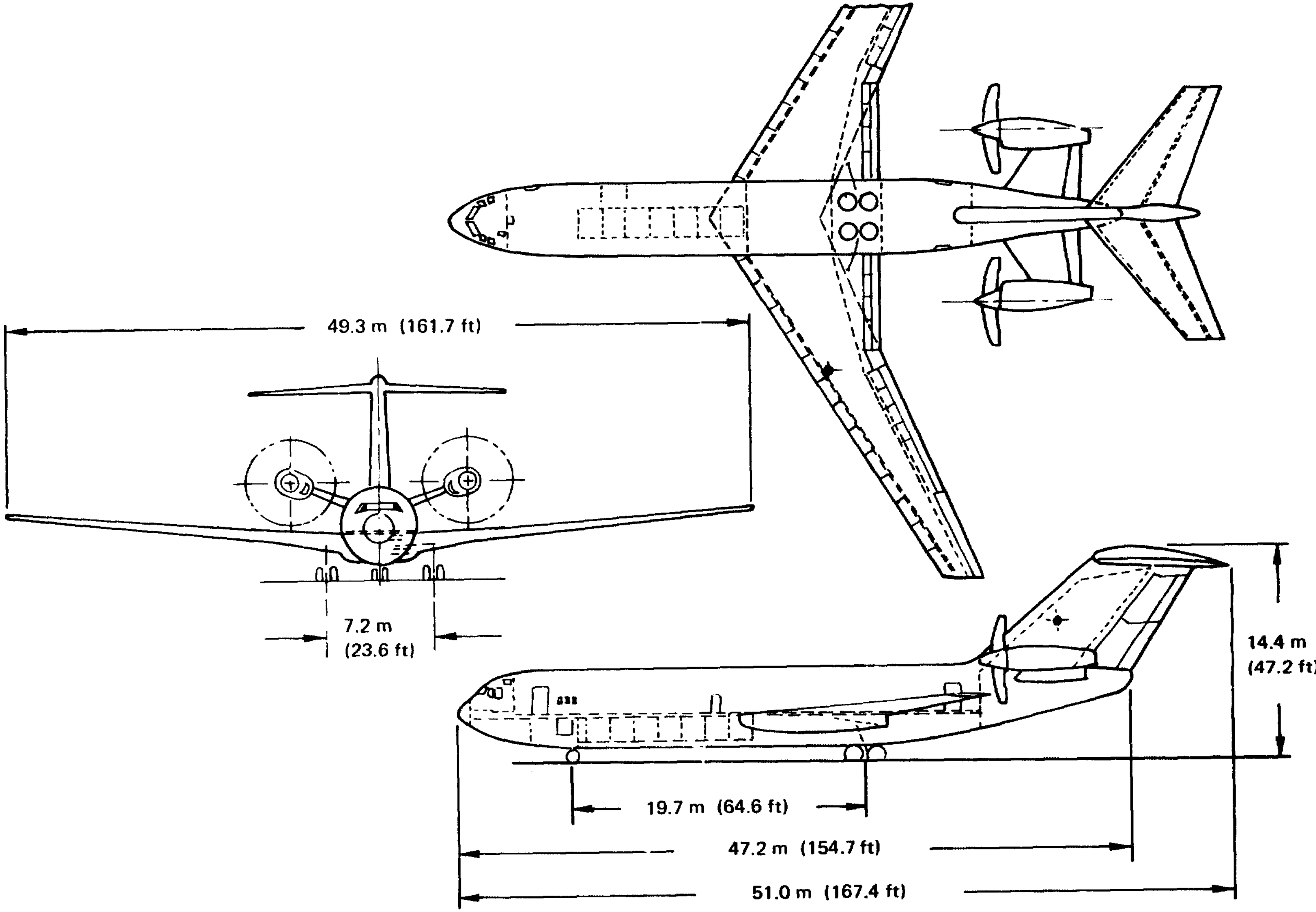


*Figure 14 General Arrangement, Aft-Mounted Prop-Fan*

*Table III 767-764 Aft-Mounted Prop-Fan Airplane Characteristics and Performance*

| | | |
|---|---|---|
| Weights | TOGW, kg (lb) | 123 970 (273 300) |
| | OEW, kg (lb) | 84 690 (186 710) |
| | Landing weight (mission), kg (lb) | 107 930 (237 950) |
| | (maximum), kg (lb) | 112 300 (247 580) |
| | Payload, pass./kg (pass./lb) | 180/16 738 (180/36 900) |
| | Max fuel capacity | 66 680 (147 005) |
| | C.G. limits, % MAC | 20 fwd, 52 aft |
| | T/W equivalent | .279 |
| | W/S, $N/m^2$ ($lb/ft^2$) | 5008.3 (104.6) |
| Performance | Still air range, km (nmi) | 3333.6 (1800) |
| | Cruise Mach number | 0.80 |
| | Cruise altitude, m (ft) | 10 970 (36 000) |
| | Range factor, km (nmi) | 25 600 (13 820) |
| | L/D average cruise | 16.41 |
| | SFC, kg/kN·sec (lb/hr/lb) | 0.0154 (0.545) |
| | TOFL, m(ft) | 1397 (4584) |
| | C.G. position, % MAC | 20 |
| | $V_{APP}$, m/sec (KEAS) | 65 (126) |
| | Block fuel, kg (lb) | 10 216 (35 750) |
| | Reserves, kg (lb) | 6510 (14 350) |
| | Total fuel, kg (lb) | 22 980 (50 660) |
| | Block fuel, kg/pass. km (lb/pass. nmi) | 0.0270 (0.110) |
| Power-plants | Number | 2 |
| | Type | Scaled P&W STS 476 |
| | Power | 23 110 kW (30 990 shp) |
| Body | Length, m (in.) | 47.14 (1856) |
| | Maximum diameter, m (in.) | 5.38 (211.6) |
| | Accommodations | 180 passengers–10% 1st, 90% tourist<br>7 LD-3 containers, 35.79 $m^3$ (1264 $ft^3$) |
| Landing gear, m (in.) | Nose | (2) -0.86x0.28 (34x11) |
| | Main | (8) -1.09x0.42 (43x16.5) |
| | Truck size | 1.32x0.97 (52x38) |
| | Oleo stroke (extended to static) | 0.51 (20) |

| Wing and empennage | | Wing | Horizontal tail | Vertical tail |
|---|---|---|---|---|
| | Area, $m^2$ ($ft^2$) | 242.8 (2613) | 72.8 (783.56) | 66.7 (717.73) |
| | Aspect ratio | 10 | 4.0 | 0.8 |
| | Taper ratio | 0.353 | 0.4 | 0.65 |
| | c/4 sweep, deg | 30 | 35 | 45 |
| | Incidence, deg | 1 | – | – |
| | Dihedral, deg | 5 | -3 | – |
| | t/c, % | 2 | 10.5 | 12 |
| | MAC, m (in.) | 5.303 (208.76) | 4.527 (178.24) | 9.266 (364.82) |
| | Span, m (in.) | 49.270 (1939.77) | 17.064 (671.80) | 7.304 (287.55) |
| | Tail arm, m (in.) | – | 20.778 (818.01) | 14.347 (564.84) |
| | Tail vol coefficient | | 1.175 | 0.080 |

1 Wing incidence: SOB 3.75
MAC 2.00
Tip -1.00

2 Wing t/c %: SOB 13.1 (total chord)
BL407.6 10.5 (const outbd)

substantially increasing the required horizontal tail area. Even then the forward c.g. takeoff rotation condition could be met only by putting control surfaces on the engine mounting struts, taking advantage of the slipstream for added control power.

## 3.4 COMPARATIVE DISCUSSION

For the design mission, the block fuel reductions fall far short of the 17.6% decrement that might have been expected on the basis of specific fuel consumption alone. The reasons for the shortfall are the added drag and weight associated with the prop-fan installation.

### 3.4.1 DRAG

Table IV shows a breakdown of drag differences among the three airplanes. The -762 wing-mounted prop-fan design has about 7% more wing area than the others because of the $C_{L_{MAX}}$ penalty for locating the nacelles on the wing leading edge. The overall friction drag is 6.3% higher than the turbofan's as a result of the added wing area, added empennage area, and extra friction in the elevated q of the slipstream over the wing. The aft-mounted prop-fan has substantially larger tail surfaces and engine struts.

The effect of the higher Mach number in the slipstream of the -762 was estimated by using a weighted average of the drag rise Mach numbers of the immersed and unimmersed portions of the wing. The $\Delta M$ of -0.012 results in a drag rise penalty of 10 counts at fixed $C_L$. In addition, the position of the nacelle on the wing increases the parasite drag due to lift. The combined effect of the two penalties is to reduce the $C_L$ for best L/D slightly.

### 3.4.2 WEIGHTS

Table V is a comparative summary of weight differences. The most dramatic differences are due to effects of the high propeller noise: 2670 kg (5880 lb)

*Table IV Drag Difference Summary*

| Item | Turbo-Fan 767-761 | Wing-Mounted Prop-Fan 767-762 | Aft-Mounted Prop-Fan 767-764 |
|---|---|---|---|
| Wing area, $m^2$ ($ft^2$) | 243.20 (2618) | 260.77 (2807) | 242.75 (2613) |
| Parasite area, $m^2$ ($ft^2$) | 4.062 (43.72) | 4.318 (46.5) | 4.503 (48.5) |
| At $C_L$ = 0.5 and M = 0.8: | | | |
| $C_{D_{PARASITE}}$ | 0.0167 | 0.0166 | 0.0186 |
| Total $C_D$ | 0 0275 | 0.0289 | 0.0294 |
| $\Delta C_D$ (ref -761) | – | +0.0014 | 0.0019 |
| $\Delta C_D$ BREAK-DOWN: parasite | – | –0.0001 | 0.0019 |
| $\Delta C_D$ BREAK-DOWN: polar shape | – | +0.0005 | 0 |
| $\Delta C_D$ BREAK-DOWN: drag rise | – | +0.0010 | 0 |
| L/D | 18.18 | 17.3 | 17.01 |
| $C_D \times S$ $m^2$ ($ft^2$) | 6.69 (71.99) | 7.54 (81.12) | 7.14 (76.82) |

*Table V   Summary of Weight Differences*

| Item | | 767-761 t/f | 767-762 t/p | 767-764 aft t/p |
|---|---|---|---|---|
| Wing | Area | 243.2 $m^2$ (2618 $ft^2$) | 260.8 $m^2$ (107.2%) (2807 $ft^2$) | 242.8 $m^2$ (99.8%) (2613 $ft^2$) |
| | Weight | 17 050 kg (37 580 lb) | 18 470 kg (108.4%) (40 720 lb) — Flutter | 18 570 kg (109.0%) (40 940 lb) — Loss of bending relief |
| Empennage | Area | 100.3 $m^2$ (1080 $ft^2$) | 119.4 $m^2$ (119.0%) (1285 $ft^2$) | 149.5 $m^2$ (149.1%) (1610 $ft^2$) |
| | Weight | 3030 kg (6690 lb) | 3710 (122.4%) (8180 lb) — Destabilizing effect of propellers | 4530 (149.5%) (9990 lb) — Short-coupled (aft engines = aft cg) |
| Body weight | | 13 720 kg (30 250 lb) | 16 470 kg (120.0%) (36 310 lb) — Cabin noise reduction | 15 840 kg (115.5%) (34 938 lb) — Engine strut support structure; accustic fatigue |
| Propulsion system | Size | 166 310 N (37 400 lb) | 22 722 kw (30 460 shp) | 23 110 kw (30 980 shp) |
| | Weight | 8770 kg (19 340 lb) | 13 450 kg (153.4%) (29 652 lb) | 13 790 kg (157.2%) (30 400 lb) |
| Operating empty weight | | 75 050 kg (165 480 lb) | 83 710 kg (111.5%) (184 540 lb) | 84 690 kg (112.8%) (186 710 lb) |
| Maximum taxi weight | | 116 260 kg (255 300 lb) | 122 960 kg (105.9%) (271 080 lb) | 124 860 kg (107.5%) (275 269 lb) |



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were added to the body structure of the wing-mounted prop-fan to reduce the cabin interior noise level to that of the turbofan, costing about 2% in block fuel at the design range; 808 kg (1780 lb) were added to increase the skin thickness of the aft body and fin of the aft-mounted prop-fan to prevent sonic fatigue, costing 1% in block fuel.

Other major differences are the increased empennage areas for the prop-fan airplanes and the higher weight of the prop-fan propulsion systems associated with the gearboxes and propellers.

# 4.0 SENSITIVITY ANALYSIS

## 4.1 PROPULSION SYSTEM WEIGHT

The change in prop-fan airplane characteristics due to possible changes in propulsion system weight are shown in table VI. The changes in takeoff gross weight (TOGW), operating empty weight (OEW) and block fuel are the changes between sized airplanes with and without the propulsion system weight change (i.e., cycled differences). This sensitivity is very linear; for a 20% change in propulsion system weight the changes in TOGW, OEW and block fuel would be doubled.

## 4.2 PROPELLER EFFICIENCY

Incremental changes in propeller efficiency in cruise of -0.05 and -0.10 were assessed on the wing-mounted prop-fan. The results are summarized in table VII.

A reduction in propeller efficiency has two major effects. First, the engine must increase in size to restore the cruise thrust and retain the optimum airplane size for minimum block fuel. Second, the overall specific fuel consumption is increased directly by the percentage change of propeller efficiency. This latter effect produces 80% of the change in block fuel, the remainder being caused by resizing the airplanes to meet the mission performance with the larger engines and heavier fuel load. The table shows that the sensitivities of TOGW, OEW, and block fuel to changes in propeller efficiency are nearly linear. The aft-mounted version of the prop-fan showed similar results to the wing-mounted prop-fan.

A reduction of 5% in propeller efficiency would effectively eliminate all potential fuel savings of the prop-fan relative to the turbofan airplane and emphasizes the importance of obtaining as high a propeller efficiency in cruise as possible.

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*Table VI Sensitivity to Propulsion System Weight*

| Change to prop system, % | +10 | |
|---|---|---|
| Airplane | Wing-mount prop-fan | Aft-mount prop-fan |
| Change to TOGW, % | +2.5 | +2.5 |
| Change to OEW, % | +3.2 | +3.2 |
| Change to block fuel, % | +1.8 | +1.8 |

*Table VII Sensitivity to Propeller Efficiency (Wing-Mounted Prop-Fan)*

| Change in prop efficiency, % | –5 | –10 |
|---|---|---|
| Change in TOGW, % | +3.9 | +8.3 |
| Change in OEW, % | +3.5 | +7.6 |
| Change in block fuel, % | +8.1 | +16.9 |

### 4.3 PROPELLER DISK LOADING AND LOCATION

The sensitivities of the 767-762 wing-mounted prop-fan to changes in propeller disk loading and in the spanwise distance of the nacelle from the side of the body were also investigated. These studies indicated that the present arrangement and propeller diameter were very close to optimum. No substantial improvement in fuel economy or weight could be expected from adjusting them.

# 5.0 ECONOMICS

## 5.1 DIRECT OPERATING COST ANALYSIS METHOD

Direct operating costs were calculated by the 1976 Boeing DOC Method, an updated version of the 1967 ATA formula. The components of DOC are crew pay, fuel, insurance, airframe maintenance, engine maintenance, maintenance burden, and depreciation.

## 5.2 FIRST COSTS

Sales price estimates were based on a production quantity of 600 airplanes with a peak production rate of eight airplanes per month. Sales price calculations utilized cash receipts, cash expenditures, airplane rollout, and delivery schedule for a reasonable return on investment for the airplane manufacturer. Cash receipts were based upon a selected airline payment and ordering schedule while cost expenditures were based upon the airplane manufacturer's cost expenditures. Airplane costs for nonrecurring and recurring production blocks were estimated by each cost element, such as engineering, tooling, production labor, and materials for major airframe components, such as wing, body, empennage, landing gear, propulsion nacelle, and systems. Differences due to the unique airframe weight distribution for each model can thus be recognized in the cost estimate and consequently reflected in the airplane price. Generally, an increase in airframe weight will result in lower dollars per pound depending on distribution of weight by airplane section.

Prop-fan propeller and gearbox prices were provided by Hamilton Standard. The turbofan engine price was obtained by using a dollars per pound of thrust trend line for engines currently in service. This was shifted to pass through a point for the Pratt & Whitney JT10-D2, which is considered representative of the price of 1985 technology engines. On the basis of an estimate by Pratt & Whitney (ref. 3), the prop-fan core engine prices were taken to be 86% of the values corresponding to "equivalent thrust" turbofans.*

## 5.3 PROPELLER AND GEARBOX MAINTENANCE COST

Maintenance costs for the prop-fan are independent of the average time per flight. These costs include the propeller controls, oil tank, and oil cooler.

Using $9.00 per hour as the labor rate, the maintenance cost (parts and labor) per engine flight-hour is $2.97 for a 6.1 m (20 ft) diameter prop-fan. Airline current experience on the older technology propeller/gearbox combination of the Lockheed Electra and Convair 540, extrapolated to the size and rating of the engine on the wing-mounted prop-fan, is about $19.22 per flight-hour. The 85% reduction by Hamilton Standard is attributed to design simplification, better modularity (permitting removal of individual blades instead of the complete rotor, for example) and increases in mean time between failures of major modules by factors of 4 to 15.

## 5.4 ESTIMATED DIRECT OPERATING COSTS

Figure 15 shows the DOC of the two prop-fan airplanes relative to the reference turbofan for ATA ranges of 966 and 1850 km (600 and 1150 statute miles), as functions of fuel price, using the Hamilton Standard projection of propeller and gearbox maintenance costs and the same data calculated with propeller and gearbox maintenance based on current experience with old technology turboprop aircraft. The wing-mounted prop-fan has a modest cost advantage at today's fuel price--about 8.18¢/liter (31¢/gal.) for domestic trunk airlines, corresponding to 6.34¢/liter (24¢/gal.) indexed to 1973, and a substantial one for fuel prices in the 13-16¢/liter (50-60¢/gal.) range, provided that the Hamilton Standard maintenance projection is realized.

*"Equivalent SLST" for the turboshaft core engine is the cruise SHP divided by 1.46 times lapse factors for speed and altitude.

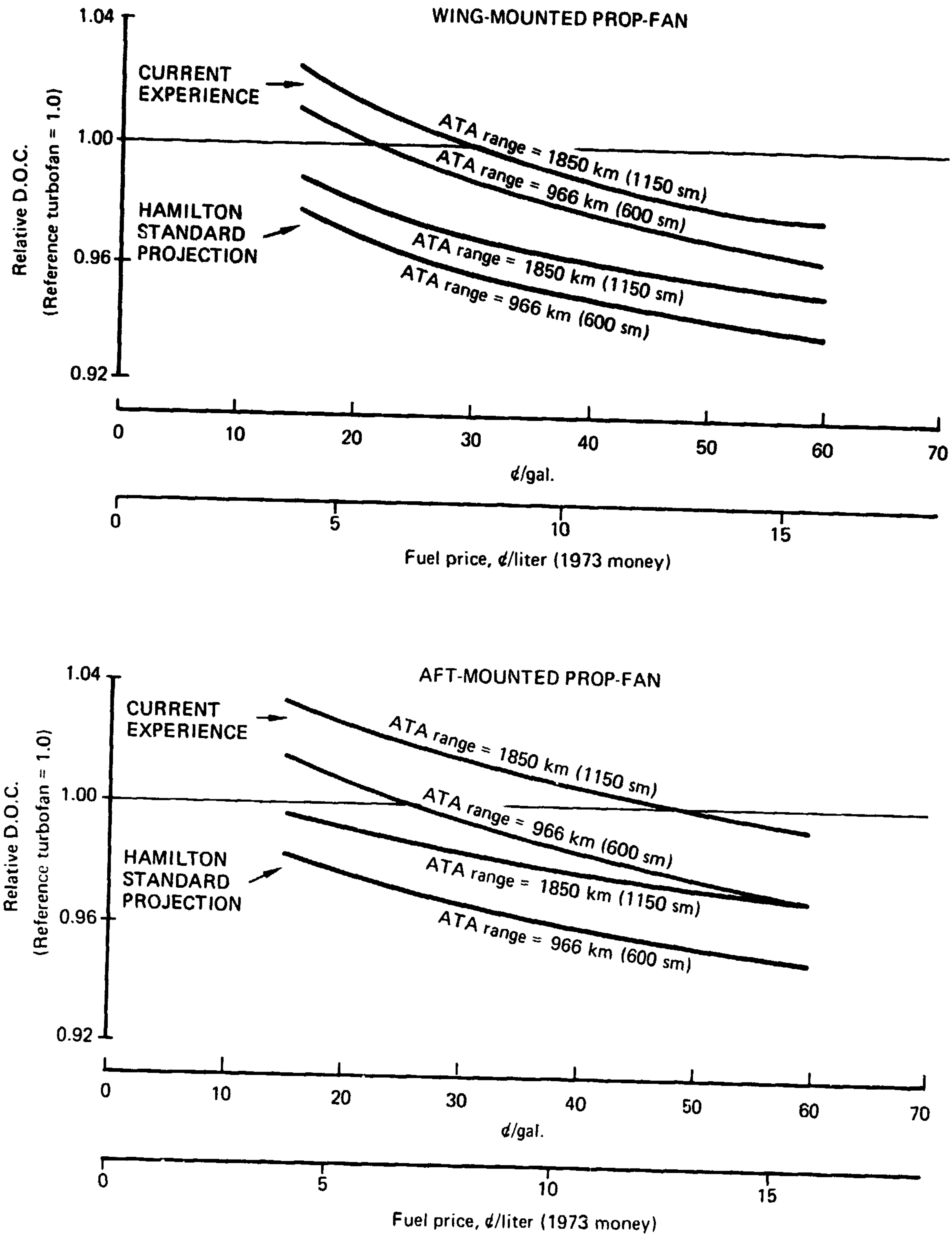


*Figure 15 Direct Operating Cost Comparison*

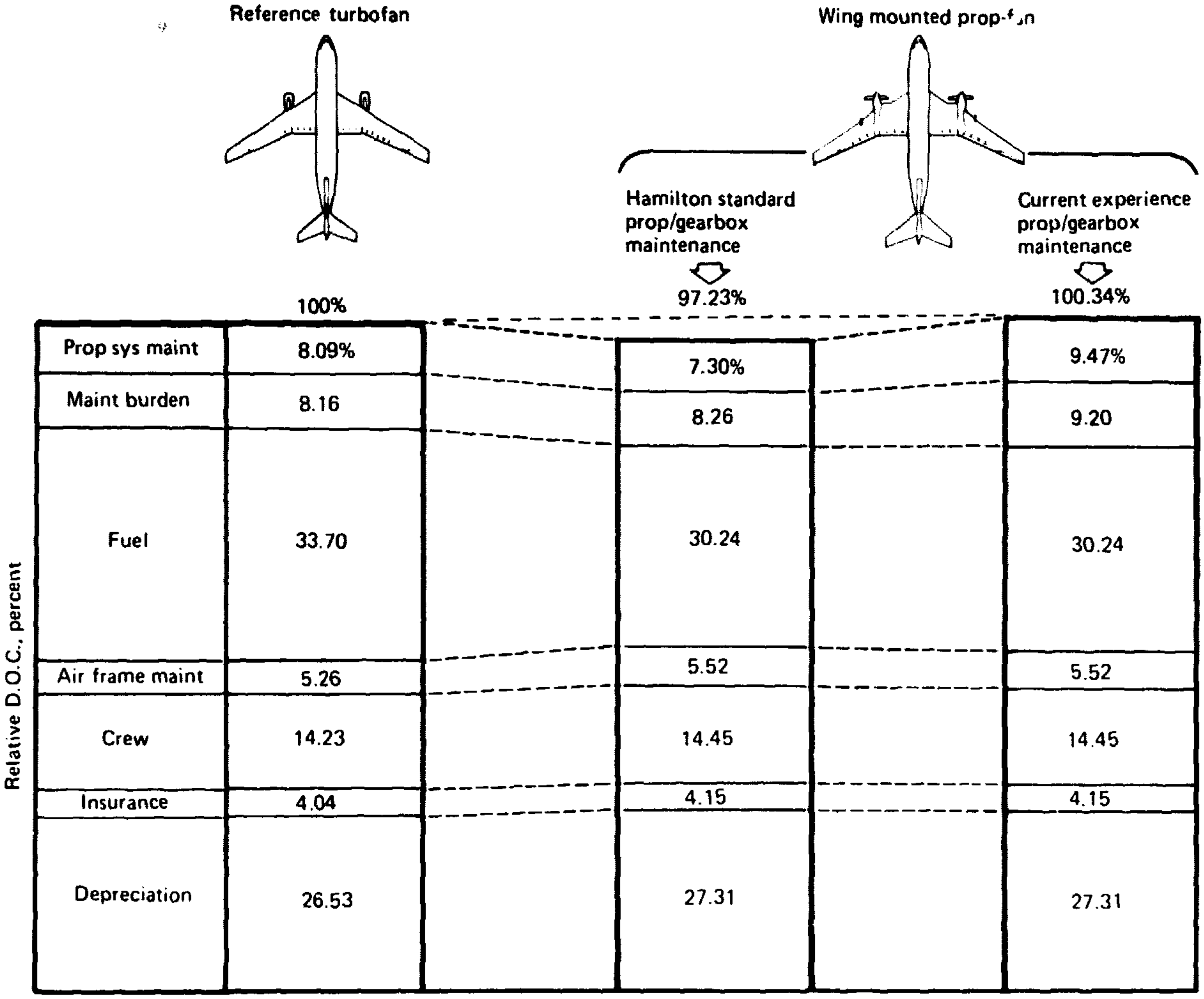


*Figure 16 Direct Operating Cost Breakdowns—1850 km (1150 sm) Trip, 30 Cents/Gallon Fuel (1973 $)*

Figure 16 shows a breakdown of the relative DOC's for the reference turbofan and the wing-mounted prop-fan for 1850 km (1150 statute miles) ATA range at 7.92¢/liter (30¢/gal.) fuel cost (1973 money). Both the Hamilton Standard and the current experience levels of propeller and gearbox maintenance are shown. Note that the effect of this item appears in the maintenance burden cost element as well as directly.

## 6.0 REFERENCES


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